Quality of Experience Under a Prospect Theoretic Perspective: A Cultural Heritage Space Use Case

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***Abstract*— Quality of experience (QoE), quantified via appropriately defined utility functions, has been widely used as a means to express user satisfaction in social systems. In such systems, subjects are usually assumed to be neutral utility maximizers, a concept that does not properly reflect the user risk-seeking behavior peculiarities. In this paper, we address the issue of incorporating and assessing the impact of visitor behavioral factors within the cultural heritage space, by exploiting the power of prospect theory. Exhibits of the cultural heritage site are organized in two main categories, namely, safe exhibits and common pool of resources (CPR) exhibits, based on their popularity and attractiveness. The latter ones are considered as nonexcludable and rivalrous resources in nature. Consequently, the obtained visitor QoE expressed via the prospect-theoretic utility function, heavily depends on the cumulative time spent by all visitors in these exhibits, thus making their behaviors and decisions interrelated, acting more like a social competitive environment. To determine visitor optimal time investment in different types of exhibits, while taking into account the potential interdependence of visitors decisions, a noncooperative game among the visitors is formulated and solved in a distributed manner, such that each visitor maximizes his own prospect-theoretic utility function. Detailed evaluation numerical results are presented, highlighting the operation and superiority of the proposed framework while providing useful insights about visitor decisions under realistic conditions and behaviors.**

***Index Terms*— Common pool resources (CPR), cultural heritage, prospect theory, quality of experience (QoE), social systems, user behavior modeling.**

I. Introduction

MODERN evolving social systems can be viewed as cyber-physical-social systems (CPSS), where users of personalized services evolve in an environment that induces constraints [1]. An individual evolves in a physical or virtual space with others, where their behavior is constrained by the former while influencing and being influenced by the latter [2]. Using behavioral insights and incorporating behavioral factors into various operating processes and approaches to examine and improve human social, cultural, and living experiences become a critical aspect of the efficiency and effectiveness of various computational methods and optimization approaches [3]. The value and impact of such social systems are typically judged by the overall achieved user experience, a metric that refers to subject's perceptions of system aspects such as utility, satisfaction, and/or efficiency [4]. User experience, often referred to as quality of experience (QoE), is considered subjective and dynamic in nature, since it is about individual perception and with respect to the system it belongs to [5], and the wider context in which it can be found [6].

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A. Related Work and Motivation

Although significant advances have been obtained and observed in the development of efficient computational tools, algorithms, and optimization methods for dealing with social systems [7], the overwhelming majority of them, have not managed to properly address the fact that individuals in real life do not necessarily behave as neutral expected utility maximizers but tend to exhibit risk-seeking or loss aversion behavior under uncertainty [8]. To deal with this challenge, in this paper, we exploit prospect theory [9] in order to integrate risk preferences in the overall optimization process and evaluation of social systems. The aim is to depict the deviations in decision making due to gain seeking or loss aversion that traditional models fail to capture [10]. The case in point of our investigation and evaluation work is that of cultural heritage spaces [11].

Cultural heritage sites, such as museums, are reflections of society as they are repositories of historical, precious and significant objects, and artifacts [12]. From a theoretical point of view, observation of the behavior of visitors within a cultural heritage space area makes it possible to identify some particularly important issues and phenomena that occur during a touring experience. These include among others the time spent by a visitor, which display area he chooses to visit, attention-span, and the ability of information to hold the attention of a visitor [13]. In this paper, the emphasis is placed on the problem of visitor optimal time management, toward increasing his satisfaction, expressed via his QoE, under a prospect theoretic perspective.

The motivation of the aforementioned objective and approach is founded on the fact that recent theories tend to consider the visitors no longer as neutral, passive subjects, but as dynamic entities. The decisions of each one may influence the decisions of the others, as in a social competitive environment [14], [15]. However, in a cultural heritage space, as opposed to other social environments, the momentum of the experience is primarily controlled by the visitor himself. Therefore a heavy burden on the visiting related decision making falls upon the visitor [16]–[18].

Recent research efforts have focused on the influential factors of visitor perceived QoE within a cultural heritage space while considering their behavioral characteristics. Ve'ron and Levasseur [19] proposed a pioneering concept of organizing the visitors into representative personas based on their behavioral characteristics as they stem from their physical movement within a cultural space, i.e., ant, butterfly, fish, and grasshopper. Goulding [20] studies the impact of visitor behavioral characteristics on the management of the service encountered in the cultural heritage spaces, identifying three main perspectives of visitor behavior, i.e., social, cognitive, and environmental. Focusing on quantifying the visitor QoE in representative functions, Sookhanaphibarn and Thawonmas [21] consider the visitor distance from exhibits and time spent observing as QoE parameters of interest. Apart from the aforementioned QoE parameters, Lykourentzou *et al.* [22] consider some intelligent recommendations to improve visitor QoE.

The intuitive principle followed in our consideration and work here can be simply stated as: "making the most of your cultural heritage space visit." This, in turn, can be more formally expressed as: optimizing the perceived QoE of visitors as expressed through a utility function that takes several parameters into consideration. The majority of relevant efforts applied in the context of cultural heritage space, usually take only physical context parameters (e.g., cultural heritage space's size, placement of the exhibits, etc.) into account, and they do not typically consider and evaluate the impact of the visitor's behavior patterns and choices, such as risks in terms of reactions to losses and/or gains, optimal visiting time, and so on [23]. In addition, when considering the cultural heritage space operator point of view, and as a by-product of our observations, evaluations, and findings, significant insights can contribute to the following principle: "knowing your visitors is an essential part of building your audience and better planning your services."

B. Contributions and Outline

In order to fill the aforementioned research gap, we consider and capture visitor realistic behavior in terms of loss aversion and gain seeking characteristics within cultural heritage spaces, while they are optimally investing their available visiting time in different types of exhibits. To the best of our knowledge, the proposed framework constitutes the first effort toward this direction in the literature. The main scientific contributions of our proposed approach that differentiate it from the rest in the relevant literature are summarized as follows.

1) The fundamental components and concepts of prospect theory are introduced and properly adapted within the research area of CPSS, with emphasis on cultural heritage spaces. Visitor decision-making under risk, as regards visiting time per exhibit, is influenced and shaped by key prospect theoretic characteristics and is in contrast to the expected utility theory where all individuals are assumed to be risk neutral with respect to their choices. This consideration allows the study and evaluation of visitor QoE under more realistic and personalized assumptions. It incorporates individual behavioral patterns that demonstrate systematic deviations from the traditionally used expected utility theory in their final decisions (Section II).
2) A cultural heritage space and its exhibits are organized into two main groups: a) safe exhibits that typically correspond to less congested ones, where the visitors are assumed to receive guaranteed satisfaction and in accordance with the visiting time invested and b) common pool of resources (CPR) exhibits, which are the most popular exhibits with possibly increased congestion and uncertain outcome in terms of visitor satisfaction (Section III-A). A key difference is that the latter (i.e., visitor satisfaction due to CPR) depends not only on the invested time decision of a specific visitor but also on that of the rest of the visitors. Each visitor's satisfaction is qualitatively and quantitatively expressed via his actual utility function, which considers the perceived satisfaction from visiting the safe and the CPR exhibits, as well as the invested visiting time per type of exhibit (Section III-B).
3) Visitor prospect-theoretic utility functions are properly formulated by considering their actual utilities, their available visiting time and their reflection to gains and losses (Section III-C). As each visitor determines the investment of his time in the safe and the CPR exhibits in an autonomous manner, the problem has been formulated as an optimization of each visitor's prospect-theoretic utility with respect to his visiting time and treated as a noncooperative game among the visitors (Section III-D).
4) The noncooperative game is solved in a distributed manner and its Nash equilibrium point is determined. The existence and uniqueness of the Nash equilibrium point demonstrate the stable operation of the considered social system at the equilibrium point while guaranteeing the satisfaction of visitors by optimally investing their available visiting time at the corresponding exhibits (Section IV).
5) A series of extensive experiments are performed to evaluate the performance and the inherent attributes of the proposed visitor-centric investment decision-making framework under prospect theory (Section V). Throughout the experimentation and evaluation study, both homogeneous and heterogeneous populations with respect to the visitor risk behavior are considered (Sections V-A and V-B, respectively). A comparative study of the proposed optimal solution against different strategy alternatives demonstrates its superiority and benefits, in terms of user satisfaction and proper system operation (Section V-A2).

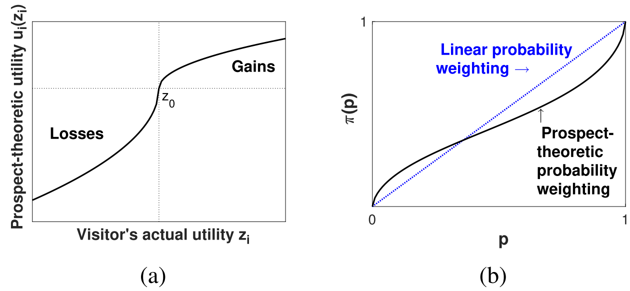
6) The role and impact of humans heterogeneity, in terms of loss aversion and sensitivity on obtained satisfaction, is examined and explained. How these behavioral parameters drive final visitors investment in CPR and safe exhibits and influence overall social system evolution is investigated (Section V-B).
7) Specific interesting observations are made and guidelines are drawn that express the point of view of both the cultural heritage site operator and of the individual visitor. These can be used toward the improvement and optimization of several objectives and metrics throughout a cultural heritage site tour (Section V-C). Finally, Section VI concludes this paper and provides interesting future research directions.

II. Behavioral Modeling Under Prospect Theory

As highlighted before, in order to address visitor subjectivity in decisions under uncertainty while capturing their gain-seeking and loss aversion behavior within the dynamic cultural heritage spaces, and formulate their representative QoE functions, the prospect theory has been adopted. Prospect theory was introduced by Kahneman and Tversky in 1979 [9], and it is a Nobel-prize-winning behavioral economics theory where the individuals make autonomous decisions under risk and uncertainty of the associated payoff of their choices, which is estimated with some probability. In contrast to the expected utility theory, where all the individuals are assumed as risk neutral with respect to their choices, the prospect theory embodies individuals' behavioral patterns, which demonstrate systematic deviations from the expected utility theory. In a dynamic environment of available choices with uncertain payoff, individuals tend to overweight low probability events and underweight high probability events [24]. Prospect theory also claims that individuals perceive greater dissatisfaction from a potential outcome of losses compared to their satisfaction from gains of the same amount.

Prospect theory has already been applied in various research fields involving decision-making under uncertainty, e.g., finance, insurance, labor markets, crowdsourcing, and so on. To the best of our knowledge, this is the first time in the literature that prospect theory is adopted and applied to determine visitor optimal visiting time in cultural heritage spaces, e.g., museum, art gallery, etc., and evaluate the achieved QoE. In the dynamic environment of cultural heritage spaces, visitor decision-making in terms of how much time to invest in each exhibit is made under risk, as their perceived satisfaction, i.e., QoE, is uncertain. It depends on multiple factors, e.g., congestion, time spent at the exhibit by other visitors, etc. Thus, the problem of determining the visiting time at an exhibit for each visitor cannot be accurately formulated simply by the traditional expected utility theory.

The behavioral model of individuals' decision-making under uncertain outcomes proposed by prospect theory has four fundamental components and characteristics: 1) reference dependence; 2) loss aversion; 3) diminishing sensitivity; and 4) probability weighting.



(a) (b)

Fig. 1. (a) Prospect-theoretic QoE. (b) Probability weighting function.

A. Reference Dependence

Under prospect theory behavioral model, cultural heritage spaces visitors determine their perceived satisfaction, i.e., QoE, from investing their visiting time in different exhibits based on the corresponding derived psychological gains or losses, with respect to a reference point. This reference point is considered as the zero point (i.e., ground truth) of visitor perceived QoE scale, and it is not necessarily synonymous with the status que, i.e., common for all visitors. In contrast, given that visitors are social humans and have different personalized expectation and aspiration levels, they have different reference points through which they express their personal and behavioral characteristics. Given the reference point z_0 and visitor time investment in the exhibits, visitors determine their prospect-theoretic probabilistic payoff, i.e., QoE, from gains (increased actual utility) or from losses (decreased actual utility), measured relatively to the reference point and depending on the time investments of all other visitors, as presented in Fig. 1(a). Visitor actual utility is formally defined in Section III-B.

B. Loss Aversion

In principle, prospect theory models the concept of loss aversion based on the empirical observation that the loss of x amount typically imposes greater dissatisfaction than the pleasure from gaining the same amount. The latter is mathematically expressed via the asymmetry in the slope of the prospect-theoretic utility function around the reference point z_0, as presented in Fig. 1(a). Prospect-theoretic utility is formally defined in Section III-C. In our context, this empirical observation is mapped to the examined problem, where the visitor prospect-theoretic utility decreases faster for a specific loss of their actual utility, compared to their corresponding increase from gaining the same magnitude of actual utility. This observation is well aligned with the realistic visitor behavior, where the potential disutility caused to a visitor under certain circumstances (e.g., missing a popular exhibit due to congestion), will be greater compared to the corresponding pleasure gained by visiting this exhibit, under the assumption of investing in both cases the same actual resource (i.e., visiting time).

C. Diminishing Sensitivity

The concept of diminishing sensitivity in prospect theory is captured in the mathematical formulation of the prospect-theoretic utility function, as presented in Fig. 1(a). The visitor prospect-theoretic utility function is concave for positive outcomes, i.e., Cartesian quadrant I, and steeper convex for negative outcomes, i.e., Cartesian quadrant III. The latter formulation stems from the empirically human behavioral patterns observed by Kahneman and Tversky [9]. They concluded that humans demonstrate risk-averse behavior in gains and risk-seeking attitude in losses, as in the latter case they are already in a deteriorated situation and they are willing to take the risk to reduce losses. The concept of diminishing sensitivity captures human's behavior under risks based on their gains and losses, in contrast to the expected utility theory which simply assumes that individuals are risk neutral.

D. Probability Weighting

The last key component of prospect theory is the psychological probability weighting of decision-makers. Specifically, humans do not weight the potential outcomes of their decisions based on their objective probabilities, as they cannot psychologically confront the extreme positive or negative outcomes [10]. Therefore, individuals tend to overestimate the likelihood of very low probability event (e.g., observing a popular exhibit under no congestion), thus overweighting unlikely outcomes ($\pi(p) > p$ for small p), while on the other hand underweight the events that are highly expected to happen ($\pi(p) < p$ for large p) [25]. The prospect-theoretic probability weighting function $\pi(p)$ of events with different likelihood to happen is presented in Fig. 1(b). The prospect-theoretic probability weighting function can be formulated as an inverse S-shaped function capturing human's psychology as described earlier.

III. Optimizing Visitor Quality of Experience

As mentioned before, cultural heritage spaces constitute social areas and systems where visitors mainly gather to observe exhibits and acquire knowledge. The time each visitor invests in his tour at the cultural heritage space directly affects his own perceived QoE, as well as the QoE of the rest of the visitors that concurrently navigate through the cultural space and observe the exhibits. The latter holds true as part of the cultural heritage space may become highly congested from visitors, whose behavior and satisfaction accordingly become interdependent.

A. Exhibits: A Common Pool of Resources

Usually, the exhibits within a cultural heritage space are categorized as two main classes, i.e., the most popular and the less popular. The less popular ones are characterized by low visitor congestion, and thus, the visitor who selects them enjoys a quite stable satisfaction overall, since he will not be adversely influenced by too many visitors. Consequently, we claim that he will perceive a "safe" QoE, according to the time that he invests. Thus, in the following, the less popular exhibits of a cultural heritage space are characterized as a safe resource from the visiting time investment perspective of the individuals/visitors. On the other hand, the most popular exhibits are subject to possibly variable and in some cases high visitor congestion. Therefore, the most popular exhibits of a cultural heritage space are considered as a CPR given that they are nonexcludable, i.e., all visitors have the right to access and observe them, while simultaneously they are rivalrous or subtractable, i.e., their observation by one visitor reduces the ability to be observed by another [11]. If visitors selfishly make the decision to spend an increased visiting time at CPR exhibits, this will result in suboptimal outcomes for the entire set of visitors that concurrently observe the specific exhibits. The latter phenomenon will conclude to the "failure" of CPR exhibits as none of the visitors will be satisfied. This concept is well known in the literature as the "Tragedy of the Commons" [26], [27].

During a cultural heritage space visit, each visitor has an available actual visiting time t_i^{Max} that he is willing to spend toward enjoying his tour via observing the available exhibits, both CPR and safe. For simplicity in the presentation and without loss of generality, in the following analysis, we consider the normalized visiting time set $T_i = [0, 1]$, where the upper bound t_i^{Max} is assumed to be equal to one for all the considered visitors. Each visitor may invest part of his overall visiting time, denoted by t_i, $t_i \in T_i$, to observe CPR exhibits and his remaining time $(t_i^{\text{Max}} - t_i)$ to visit safe exhibits. The goal of each visitor is to determine in an autonomous manner the investment of his time to the safe and the CPR exhibits, so as to maximize his perceived QoE from his visit to the cultural heritage space. Assuming that there exist N visitors, where $\aleph = \{1, 2, \ldots N\}$ denotes their set, and following the concept of the Tragedy of the Commons, the probability of failure of the CPR exhibits is denoted by $p(t_T)$, where $t_T = \sum_{i=1}^{N} t_i$ is the total investment of all the N visitors at the CPR exhibits.

Assumption 1: The CPR exhibits are characterized by the following properties.

1) The probability of failure $p(t_T)$ is convex, strictly increasing and twice continuously differentiable with respect to the aggregate investment by the visitors $t_T \in [0, 1]$ with $p(1) = 1$ and $p(t_T) = 1, \forall t_T \geqslant 1$.
2) Visitor's i strategy set of visiting time to the CPR exhibits is $T_i = [0, 1], \forall i \in \aleph$.

Some examples of CPR exhibits probability of failure are the linear function (i.e., $p(t_T) = t_T$) or the exponential function (i.e., $p(t_T) = t_T^g$, where g is a positive real constant) and can be chosen based on the sensitivity of the CPR exhibits to the failure. It is noted that if CPR exhibits fail due to overinvestment by the visitors then none of them will receive any benefit from the CPR. Thus, their perceived QoE from visiting the CPR exhibits will be zero.

B. Actual Utility

In this section, the visitor actual utilities from investing his available visiting time in CPR and safe exhibits are formulated. The perceived visitor actual utility from each type of exhibits is differentiated given the characteristics and nature of the exhibits. Specifically, the actual utility gained from safe exhibits is proportional to the invested visiting time by the visitor under the realistic assumption that those exhibits are not congested due to their nature and the more time the visitor spends to those exhibits, the more satisfaction he gets. On the other hand, CPR exhibits are coshared among multiple visitors, thus each visitor's actual utility depends on the visiting time of all the visitors that concurrently observe the CPR exhibits.

Based on the above-mentioned discussion, the visitor's i perceived actual utility $z_i(t_i)$ from safe exhibits is a linear function with respect to visitor's invested time $(t_i^{\text{Max}} - t_i)$ in the safe exhibits and is given as follows:

$$z_i^{\text{SAFE}}(t_i) = w_i\left(t_i^{\text{Max}} - t_i\right) \tag{1}$$

where $w_i = e_w I_i$ expresses the overall importance of safe exhibits with respect to visitor i, as the combined effect of the following two factors. The first one denoted by $e_w, e_w \in [0, 1]$ refers to safe exhibits weight, reflecting their historical importance, as dictated by cultural heritage experts. The second one, denoted by I_i, $I_i \in [0, 1]$, represents the visitor's subjective interest in the specific safe exhibits.

With respect to CPR exhibits, visitor actual utility depends on both the time invested to observe them by visitor i and the corresponding invested time of the rest of the visitors. Therefore, the visitor's i actual utility from CPR exhibits is given as follows:

$$z_i^{\text{CPR}}(t_i) = w_i^c \frac{t_i}{t_T} F(t_T) \tag{2}$$

whereas before t_i refers to the visiting time invested by visitor $i, i \in \aleph$ at CPR exhibits, $t_T = \sum_{i=1}^{N} t_i$ is the total invested time at CPR exhibits by all visitors and $F(t_T)$ is the production function expressing the return of CPR exhibits to visitors based on their total investment and is specifically defined in the following. Also, note that $w_i^c = e_w^c I_i^c$ expresses the corresponding overall CPR exhibits importance for user i and is defined similar to the corresponding definition of the safe exhibits importance w_i. That is, $e_w^c, e_w^c \in [0, 1]$ refers to the CPR exhibits' weight, while I_i^c, $I_i^c \in [0, 1]$, represents the visitor's subjective interest in the specific CPR exhibits.

Assumption 2: The production function $F(t_T)$ is assumed to be concave [28] with respect to the total time investment t_T, with $F(0) = 0$, $F'(0) > w_i$ and $F'(Nt_i^{\text{Max}}) < 0$.

The above-mentioned assumption states that the initial investment of visiting time t_i at CPR exhibits is more appealing to visitors compared to safe exhibits, as the first ones provide larger actual utility to visitors for small invested visiting time. On the other hand, if visitors as a whole invest increased visiting time at CPR exhibits, this strategy leads to suboptimal outcomes, as the perceived actual utility decreases due to $F'(Nt_i^{\text{Max}}) < 0$. In other words, if the total investment of visiting time t_T by all visitors at CPR exhibits exceeds a threshold, then it becomes less attractive to visitors to invest their time at CPR exhibits. Based on the above, we define the rate of return function, as follows:

$$r(t_T) = \frac{F(t_T)}{t_T}. \tag{3}$$

Assumption 3: The rate of return function $r(t_T)$ is nonincreasing, monotonic, concave, twice continuously differentiable with respect to $t_T, t_T \in [0, 1]$ and $r(t_T) > 1$.

CPR exhibits are typically the most popular exhibits of a cultural heritage space thus experts have identified their great historical importance, i.e., we can consider $e_w^c = 1$, and visitors have also great interest in visiting them, i.e., $I_i^c = 1, \forall i \in \aleph$. Therefore, in the following, we assume for CPR exhibits that $w_i^c = 1, \forall i \in \aleph$. Based on this and combining (2) and (3), we conclude to the following simplified form of visitor actual utility from CPR exhibits:

$$z_i^{\text{CPR}}(t_i) = t_i r(t_T). \tag{4}$$

The total actual utility that a visitor perceives a linear combination of the utility gained by observing both safe and CPR exhibits. Thus, the total actual utility can be formulated via combining (1) and (4) as follows:

$$\begin{aligned} z_i(t_i) &= z_i^{\text{SAFE}}(t_i) + z_i^{\text{CPR}}(t_i) \\ &= w_i\left(t_i^{\text{Max}} - t_i\right) + t_i r(t_T). \end{aligned} \tag{5}$$

C. Prospect-Theoretic Utility

The prospect-theoretic utility of visitor $i, i \in \aleph$ in a cultural heritage space is defined as follows:

$$u_i(z_i) = \begin{cases} (z_i - z_0)^{a_i}, & z_i \geqslant z_0 \\ -k_i(z_0 - z_i)^{b_i}, & z_i < z_0 \end{cases} \tag{6}$$

where z_i is the visitor's $i, i \in \aleph$ actual utility as defined earlier in (5) and z_0 denotes the reference point of visitor's perceived prospect-theoretic utility. We define the reference point z_0 for each visitor $i, i \in \aleph$ as the actual utility that he gets from investing his total visiting time at safe resources, as follows:

$$z_0 = w_i t_i^{\text{Max}}. \tag{7}$$

Note that for simplicity in the presentation and without harming the validity of our analysis, we have dropped t_i from the notation of $z_i(t_i)$. Moreover, the parameters a_i, b_i where $a_i, b_i \in (0, 1]$ express the sensitivity of visitors to the gains and losses of their actual utility z_i, respectively. Specifically, small values of parameter a_i reflect greater increase of the prospect-theoretic utility u_i for small values of the actual utility z_i. Therefore, a visitor i with smaller value of parameter a_i experiences superior prospect-theoretic utility u_i compared to a visitor j who has larger value of a_j, $a_i < a_j$ considering the same amount of actual utility. Thus, the risk seeking behavior of a visitor in losses and his risk averse behavior in gains is reflected by small values of parameter a_i in his prospect-theoretic utility u_i. Following similar reasoning, the small values of parameter b_i imply higher decrease of visitor prospect-theoretic utility for small values of z_i and close to the reference point z_0. In this paper, we consider that visitors follow analogous behavior in losses and gains, i.e., $a_i = b_i$.

Furthermore, the parameter $k_i, k_i \in [0, \infty)$ reflects the impact of losses compared to gains in visitor's prospect-theoretic utility. Specifically, if $k_i > 1$, the visitor weights losses more than gains, thus he illustrates a loss averse behavior as he is resistant to lose part of his actual utility z_i. The exact opposite holds true when $0 \leqslant k_i \leqslant 1$, where the visitor weights gains more than losses, thus presenting an aggressive gain seeking behavior. Note that the use of different parameters a_i, k_i for various visitors allows taking into account with high granularity all personal characteristics of every visitor. If a homogeneous population is assumed, then we would consider $a_i = a$ and $k_i = k$ for every visitor i, $i \in \aleph$.

If CPR exhibits do not fail due to overinvestment of visitor time, then each visitor perceives an actual utility given by (5). In this case, the actual perceived utility is greater than the reference point z_0, i.e., $z_i \geqslant z_0$ as at the reference point the visitor i makes zero-time investment at CPR exhibits, i.e., $t_i = 0$. Therefore, via subtracting the reference point $z_0 = w_i t_i^{\text{Max}}$ from (5) and shaping the result according to first branch of (6), we have $u_i(z_i) = [t_i(r(t_T) - w_i)]^{a_i}$. On the other hand, if CPR exhibits fail to serve visitors due to very high congestion, the second term of (5) is zero and the visitor's actual utility z_i stems only from the perceived satisfaction from safe resources. Therefore, the visitor's perceived actual utility is written as $z_i(t_i) = w_i(t_i^{\text{Max}} - t_i)$ and it is less than the reference point z_0, i.e., $z < z_0$, where $z_0 = w_i t_i^{\text{Max}}$. Thus, the second branch of (6) can be written as $u_i(z_i) = -k_i(w_i t_i)^a$.

Following the aforementioned argumentation, we can readily conclude that the visitor's prospect-theoretic utility as presented in (6) can be rewritten as

$$u_i(z_i) = \begin{cases} [t_i(r(t_T) - w_i)]^{a_i}, & z_i \geqslant z_0 \\ -k_i(w_i t_i)^{a_i}, & z_i < z_0. \end{cases} \tag{8}$$

Moreover, by defining $\overline{r}(t_T) \triangleq (r(t_T) - w_i)^{a_i}$ for notational convenience, (8) can be written as

$$u_i(z_i) = \begin{cases} t_i^{a_i}\overline{r}(t_T), & z_i \geqslant z_0 \\ -k_i(w_i t_i)^{a_i}, & z_i < z_0. \end{cases} \tag{9}$$

CPR exhibits failure depends on the total invested visiting time at them by all visitors. Given that the probability of CPR exhibits failure is $p(t_T)$ as defined before, then the probability to survive and serve the visitors is $(1 - p(t_T))$. Therefore, considering the probability of CPR exhibits failure $p(t_T)$, (9) can be written equivalently as follows:

$$u_i(z_i) = \begin{cases} t_i^{a_i}\overline{r}(t_T), & \text{with probability } 1 - p(t_T) \\ -k_i(w_i t_i)^{a_i}, & \text{with probability } p(t_T). \end{cases} \tag{10}$$

Accordingly, each visitor's expected prospect-theoretic utility based on all visitor's visiting time investment $\mathbf{t} = [t_1, t_2, \ldots, t_i, \ldots, t_N]$ is given in the following:

$$\begin{aligned} \mathbb{E}(u_i) &= t_i^{a_i}\overline{r}(t_T)(1 - p(t_T)) + (-k_i(w_i t_i)^{a_i})p(t_T) \\ &= t_i^{a_i}\left[\overline{r}(t_T)(1 - p(t_T)) - k_i w_i^{a_i} p(t_T)\right] \\ &\triangleq t_i^{a_i} f_i(t_T) \end{aligned} \tag{11}$$

where $f_i(t_T) \triangleq \overline{r}(t_T)(1 - p(t_T)) - k_i w_i^{a_i} p(t_T)$ is defined as the effective rate of return of CPR exhibits. The impact of visitor related personalized parameters a_i and k_i, where $a_i \in (0, 1]$ and $k_i \in [0, \infty)$, on the final decision making process is exploited in detail later in Section V.

D. QoE Optimization: Problem Formulation

The goal of each visitor i within a cultural heritage space is to maximize his perceived QoE from his tour via sophisticatedly and selfishly investing his visiting time t_i and $(t_i^{\text{Max}} - t_i)$ at CPR and safe exhibits, respectively. Based on (11), this problem can be formulated as a maximization problem of each visitor's prospect-theoretic utility function considering the physical limitations of his visiting time as follows:

$$\max_{t_i \in T_i} \mathbb{E}(u_i) = t_i^{a_i} f_i(t_T). \tag{12}$$

The above-mentioned maximization problem can be confronted as a noncooperative game among visitors who act as rational players making the optimal decisions about themselves in a selfish and distributed manner. Let $G = [N, \{T_i\}, \{\mathbb{E}(u_i)\}]$ denote the noncooperative game among the N visitors, where each visitor's strategy space is T_i and his payoff is his expected utility function $\mathbb{E}(u_i)$. Toward solving the noncooperative game, the concept of Nash equilibrium is adopted. The Nash equilibrium of the noncooperative G is the vector of visitor visiting time at CPR exhibits $\mathbf{t}^* = [t_1^*, t_2^*, \ldots, t_i^*, \ldots, t_N^*]$, where no visitor has the incentive to change his own strategy given the strategies of the rest of the visitors. In the following, we adopt the notation $\widehat{\mathbf{t}^*_{-\mathbf{i}}} = [t_1^*, t_2^*, \ldots, t_{i-1}^*, t_{i+1}^*, \ldots, t_N^*]$ to refer to the visiting time vector of all visitors except visitor i at the equilibrium point.

Definition 1: The visiting time vector at CPR exhibits $\mathbf{t}^* = [t_1^*, t_2^*, \ldots, t_i^*, \ldots, t_N^*] \in T, T = T_1 \times T_2 \times \ldots \times T_N$ is a Nash equilibrium of the noncooperative game $G = [N, \{T_i\}, \{\mathbb{E}(u_i)\}]$ if for every $i, i \in \aleph$ holds $\mathbb{E}(u_i(t_i^*, \widehat{\mathbf{t}^*_{-\mathbf{i}}})) \geqslant \mathbb{E}(u_i(t_i, \widehat{\mathbf{t}^*_{-\mathbf{i}}}))$ for all $t_i^* \in T_i$.

IV. Existence and Uniqueness of Nash Equilibrium

In this section, we analytically seek the existence and uniqueness of the Nash equilibrium point of the noncooperative game $G = [N, \{T_i\}, \{\mathbb{E}(u_i)\}]$. The Nash equilibrium point is the visiting time vector $\mathbf{t}^* = [t_1^*, t_2^*, \ldots, t_i^*, \ldots, t_N^*]$ that visitors invest to observe CPR exhibits. In the following, we use the notation $t_{-i} = \sum_{j=1, i \neq j}^{N} t_j$ for the total visiting time of all visitors except visitor i. Also, $\overline{T_{-i}} = T_1 \times \ldots \times T_{i-1} \times T_{i+1} \times \ldots \times T_N$ denotes the strategy set of all visitors excluding visitor i. Let us denote the best response strategy $B_i(t_{-i}) : \overline{T_{-i}} \to T_i$ of visitor i as follows:

$$B_i(t_{-i}) = \arg\max_{t_i \in T_i} \mathbb{E}(u_i(t_i, t_{-i})), t_{-i} \in \overline{T_{-i}}. \tag{13}$$

Theorem 1: A pure Nash equilibrium (PNE) $t_i^* = B_i(t_{-i})$ of the non-cooperative game $G = [N, \{T_i\}, \{\mathbb{E}(u_i)\}]$ exists and the following properties hold true.

1) $B_i(t_{-i}) = 0$ if and only if there exists a threshold value $t_{\text{thres}} \in [0, 1]$ such that $t_{-i} \geqslant t_{\text{thres}}$.
2) $0 < B_i(t_{-i}) < 1$ and $B_i(t_{-i}) + t_{-i} < t_{\text{thres}}$, if there exists an interval $\Im \subset [0, t_{\text{thres}})$ such that $f(t_{\text{thres}}) = 0$ and $t_{-i} < t_{\text{thres}}$.
3) For $t_T = \sum_{i=1}^{N} t_i \in \Im$ then $f(t_T) > 0$ and $f'(t_T) < 0$ hold true.

Proof: The proof is obtained following similar reasoning as in [26]. For completeness, the interested reader may refer to Appendix A.

Based on Theorem 1, we have shown the existence of the PNE of the game $G = [N, \{T_i\}, \{\mathbb{E}(u_i)\}]$. In the following, we initially examine the properties of each visitor's best response strategy as presented in (13), in order to conclude to the uniqueness of Nash equilibrium.

Lemma 1: The best response strategy $B_i(t_{-i})$, as presented in (13), is single valued for $t_{-i} \in \overline{T}_{-i}$.

Proof: The proof is obtained following similar reasoning as in [26]. For completeness, the interested reader may refer to Appendix B.

Based on Lemma 1, we have shown that the best response strategy $B_i(t_{-i})$ is single valued and it should satisfy the first-order condition of $\mathbb{E}(u_i)$ as follows:

$$\frac{\partial \mathbb{E}(u_i)}{\partial t_i} = a_i t_i^{a_i - 1} f_i(t_T) + t_i^{a_i} \frac{\partial f_i(t_T)}{\partial t_T} = 0. \tag{14}$$

Based on (14), we define the function

$$g_i(t_T) \triangleq -\frac{a_i f_i(t_T)}{\frac{\partial f_i(t_T)}{\partial t_T}} = t_i \tag{15}$$

which should be satisfied by the best response strategy.

Theorem 2: The PNE of the noncooperative game $G = [N, \{T_i\}, \{\mathbb{E}(u_i)\}]$ is unique.

Proof: The proof is obtained following similar reasoning as in [26]. For completeness, the interested reader may refer to Appendix C.

V. Evaluation and Numerical Results

In this section, we provide a series of extensive numerical results evaluating the performance and the inherent attributes of the proposed visitor-centric investment decision-making framework under prospect theory. Initially, in order to gain some insight into the impact of the various prospect-theoretic key parameters related to visitor behavior, in terms of optimal time management and obtained satisfaction, we focus on a basic scenario where all visitors exhibit common risk preferences (i.e., homogeneous population). In the same basic setting, a comparative study of the proposed optimal solution demonstrates its superiority and benefits over alternative strategies. Subsequently, we investigate how visitors heterogeneity in terms of both loss aversion and sensitivity parameters (i.e., heterogeneous population) impact user satisfaction, influence the overall decision-making process of visitors, and drive their final investment in CPR and safe exhibits accordingly.

Before proceeding with the presentation of the obtained numerical results of our extensive evaluation, and in order to get more realistic observations, we describe the representative functions utilized, as they were properly parameterized through a detailed research experimentation based on data that were collected through a detailed questionnaire [29]. Specifically, the questionnaire was circulated to experts in the field of cultural heritage spaces (especially in the fields of museums and art galleries) to identify the most influential parameters on visitor QoE [29]. According to the collected and analyzed data, the key parameters that significantly impact visitor QoE could be classified into two basic sets: those that are completely controlled by a cultural heritage space (i.e., mainly related to the physical layout of exhibits), and the ones that are also related to visitors behavior and their interdependence, such as crowd density. The latter parameters are the ones of specific interest to our present study.

Note that crowd density is closely related to and influenced by, the time invested and spent by visitors at the exhibits. Consequently, the corresponding data obtained by the questionnaire were primarily exploited to shape and formulate the production function $F(t_T)$ and the rate of return function $r(t_T)$. The production function $F(t_T)$ is a concave function with respect to the total visiting time investment t_T (see Assumption 2). Accordingly, for demonstration purposes and without loss of generality, in our experimentation, we considered the quadratic function $F(t_T) = ct_T^2 + dt_T$, where $c < 0$. Representative values of the parameters c and d were obtained based on the statistical analysis of the questionnaire's answers and data, primarily with respect to crowd density (i.e., number of simultaneous visitors per square meter) and its impact on the respective achieved user satisfaction. Therefore, we concluded to the following production function $F(t_T) = -2t_T^2 + 3t_T$ and rate of return $r(t_T) = -2t_T + 3$, which is consistent with Assumption 3 as well.

A. Homogeneous Population-Common Visitor Behavior

1) Basic Properties: In this section, we initially examine visitor investment in each exhibit type (CPR or safe), considering common sensitivity and loss aversion parameters ($a_i = a, k_i = k$). The same interest in safe exhibits is assumed for each visitor, that is ($w_i = w$), unless otherwise explicitly stated. This suggests a homogeneous perception of visitors against potential resource failure. The objective of this evaluation is to study the properties and operation of the prospect-theoretic investment process between CPR and safe exhibits, by illustrating how homogeneity in visitor risk attitudes influence their time investment in CPR and corresponding expected prospect-theoretic utility.

Fig. 2 illustrates visitors optimal investment and expected prospect-theoretic utility as a function of loss aversion parameter k (horizontal axis) for different indicative values of sensitivity parameters a and w. It can be clearly observed that there is a decrease in both visitor optimal investment and expected prospect-theoretic utility as loss aversion index increases, for all different values of w and sensitivity parameter a. The time investment falls gradually as loss aversion grows because visitors become more loss averse meaning that they weight losses more than gains. This behavior makes gambling less appealing to them, and consequently, they push their investment to CPR exhibits down due to their fear for loss. The visitor expected prospect-theoretic utility shows a continuous slight decrease as a result of the corresponding drop of the investment. As the visitors invest less in CPR, it is reasonable to receive less joy from observing it. Fig. 2 also demonstrates that the lower the interest of the visitor in safe exhibits (as expressed via parameter w), the higher are both the investment in CPR and the respective utility, as expected. Small values of w declare a small interest in safe exhibits, which in turn leads to higher investments in CPR exhibits.

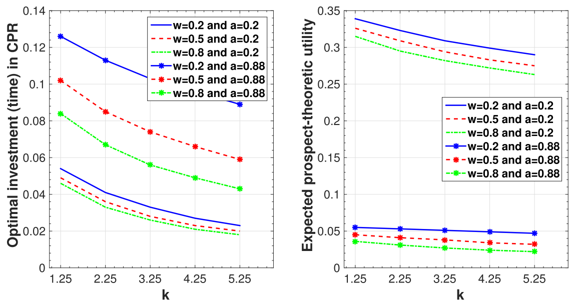


Fig. 2. Visitor optimal investment (left) and visitor expected prospect-theoretic utility (right) as function of loss aversion index k—homogeneous population.

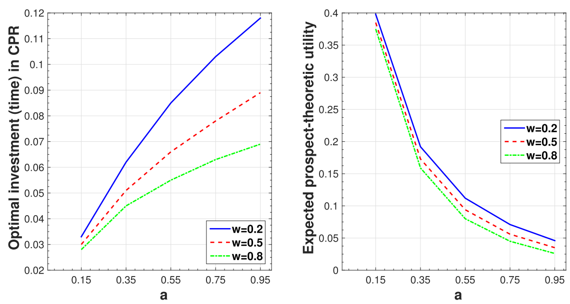


Fig. 3. Visitor optimal investment (left) and visitor expected prospect-theoretic utility (right) as function of sensitivity parameter a—homogeneous population.

Furthermore, the curves also depict that though a significant increase in visitors investment is observed as a result of the rise of the sensitivity parameter a, on the contrary, the expected prospect-theoretic utility dropped dramatically. As explained before, smaller values of a indicate a sharper increase of prospect-theoretic utility for small values of perceived actual utility. Consequently, visitors with smaller a become more prospect theoretic or in other words become risk seeking in losses and risk-averse in gains. In a nutshell, visitors with smaller a become happier compared to visitors with higher a for the same gain, or equivalently visitors with smaller a though they may invest less to CPR, they get higher satisfaction. Similar observations are confirmed from the results presented in Fig. 3 that illustrate visitor optimal investment and expected prospect-theoretic utility as a function of sensitivity parameter a, for different indicative values of parameter w. All the scenarios have been executed with visitors having identical loss aversion indices $k = 2.25$.

Fig. 4 presents the average values of optimal investment time, expected prospect-theoretic utility and perceived actual utility of five visitors with identical prospect theoretic characteristics. The figure depicts three groups of bar charts, each one representing a different loss aversion value k applied to all visitors. As can be seen from this figure, visitors with higher loss aversion spend less time in the CPR, while their expected prospect-theoretic utility is only slightly lower when compared to visitors with smaller loss aversion. Consequently, from a cultural heritage site operator point of view visitors with high loss aversion indices would be more preferable

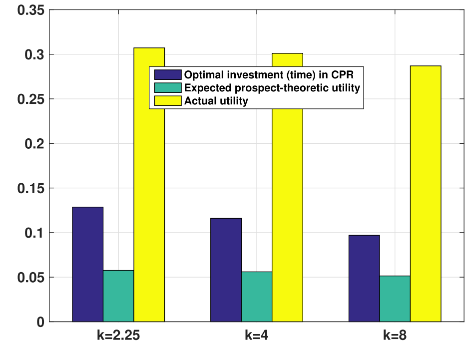


Fig. 4. Optimal investment in CPR, expected prospect-theoretic utility and actual utility for different values of loss aversion parameter k—homogeneous population.

and attractive, as they achieve almost the same utility (i.e., satisfaction) without congesting the museum since they spend less time in CPR exhibits of high popularity.

2) Comparative Results: Fig. 5 compares the performance of the proposed prospect-theoretic approach (in the following we also refer to as PT strategy) according to the optimal Nash equilibrium solution, with four alternative strategies. Specifically, the first alternative strategy (strategy 1) claims that all visitors invest their entire time in safe exhibits, which provides a baseline scenario for benchmarking purposes. The second alternative (strategy 2) divides the total optimal investment time in CPR exhibits as obtained by the Nash equilibrium of the PT approach, by the number of visitors in a uniform manner. The next alternative (strategy 3) divides the total available time of each visitor in a static manner. In particular, each visitor allocates 20% of his time to CRP exhibits and the rest 80% to safe exhibits. In the last strategy (strategy 4), each visitor allocates to CPR exhibits random time within the interval $(0, t_{\text{thresh}})$ and accordingly the remaining of his available time to safe exhibits. Fig. 5 clearly shows that the proposed PT strategy outperforms all the rest strategies. We consider strategy 1 as a reference point because both the investment time in CPR and the expected prospect-theoretic utility are zero. Regarding strategy 2, even though the total optimal time investment in CPR is considered the same with the proposed PT strategy, the latter outperforms the former with respect to the achieved expected prospect-theoretic utility by approximately 27%, which is explained by the fact that the two strategies differ in the distribution of the invested time in the CPR exhibits among the visitors. In the proposed PT strategy, the time allocated to the CPR by each visitor corresponds to the optimal time t_i^* that maximizes his prospect-theoretic utility, while in strategy 2 each visitor time investment in the CPR is obtained by diving the total optimal time t_T by the number of visitors. Furthermore, both strategies 3 and 4 result in negative values of the expected prospect-theoretic utilities as in both scenarios the total time investment t_T in the CPR exhibits exceeds the t_{thresh} value. As a consequence, the effective rate of return is negative, meaning that CPR exhibits return a nonpositive payoff to visitors and in accordance to (11) a negative value of expected-prospect theoretic utility is obtained.

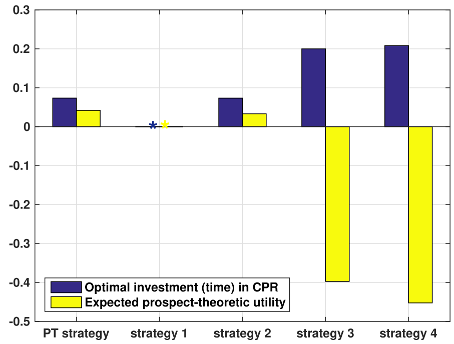


Fig. 5. Comparison of PT strategy with alternative time management strategies—homogeneous population.

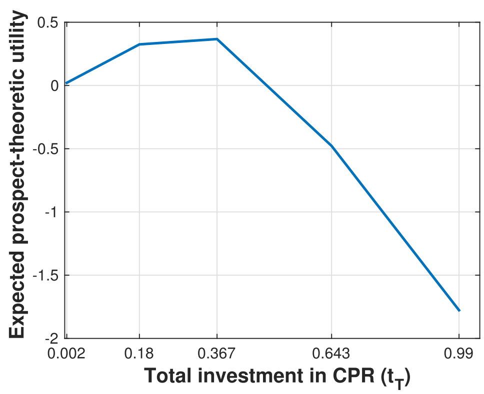


Fig. 6. Expected prospect-theoretic utility versus total investment (time) in CPR—homogeneous population.

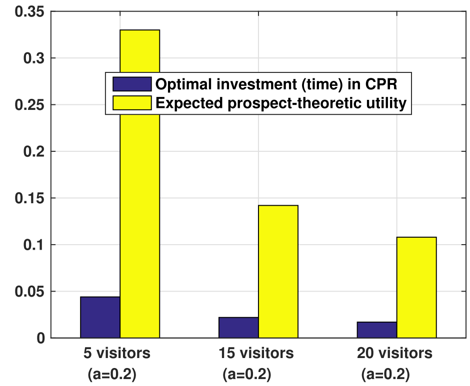


Fig. 7. Optimal investment in CPR and expected prospect-theoretic utility versus number of visitors—homogeneous population.

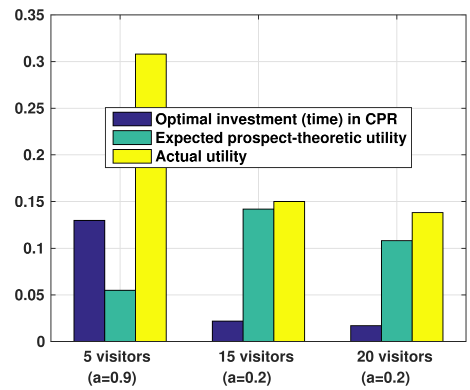


Fig. 8. Optimal time investment in CPR, expected prospect-theoretic utility and actual utility for varying number of visitors and sensitivity parameter a—homogeneous population.

Fig. 6 further demonstrates the achieved expected prospect-theoretic utility as a function of the total time t_T invested in CPR exhibits by all visitors. The key objective of this experiment and study is to demonstrate that the proposed approach (PT strategy) properly identifies the optimal time decision-making and distribution among the various visitors, in order to maximize their expected prospect-theoretic utility. The most left point in the horizontal axis corresponds to the case where visitors invest only in safe exhibits, whereas the most right point refers to the case where all visitors invest their total time in CPR exhibits. The results show that expected prospect-theoretic utility increases gradually as visitors total investment increases, reaching a maximum value at the point predicted by the prospect-theoretic approach (i.e., $t_T = 0.367$). Afterward, the corresponding utility experiences a dramatic drop, while as explained earlier when the total time investment t_T exceeds the t_{thresh}, the expected prospect-theoretic utility obtains negative values.

3) Increasing Number of Visitors: The following Fig. 7 compares three different scenarios with an increasing number of visitors (i.e., 5, 15, and 20 visitors), in terms of the average optimal visiting time per visitor and corresponding expected prospect-theoretic utility. The same sensitivity parameter $a = 0.2$ has been assumed for all visitors and for all three scenarios. The graph demonstrates that even when the number of visitors significantly increases, CPR does not fail as visitors properly adapt their decisions. Therefore, an increased number of visitors can still be supported. However, this does not come at zero cost. We notice that as the number of visitors increases, both the average optimal time investment in CPR exhibits and the expected prospect-theoretic utility of each visitor decrease indicating that visitors should decrease their visiting time in order for more subjects to have access to CPR.

Moreover, Fig. 8 illustrates how sensitivity parameter a influences visitor behavior and corresponding expected prospect-theoretic utility. The overall experimental setup is similar to the previous one, however, now the scenarios differ not only with respect to the number of homogeneous visitors but also with respect to the corresponding sensitivity parameter a. Specifically, the first scenario is executed with five homogeneous visitors of high sensitivity parameter a, whereas in the second scenario the number of visitors is tripled but they present lower a, and in the third scenario the number of visitors is further increased (quadrupled with respect to the baseline scenario) while still maintaining low sensitivity parameter a. As can be seen from the graph, the decrease of a resulted in a significant reduction of optimal investment time and an equivalent remarkable growth of the expected prospect-theoretic utility. The increased visitor sensitivity parameter causes the rise of investment in the expectation of improving the obtained satisfaction. Nevertheless, the increased visitor sensitivity parameter keeps the expected prospect-theoretic utility to low levels, whereas a significant

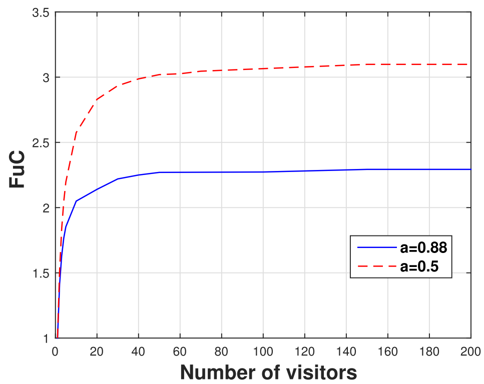


Fig. 9. FuC as a function of number of visitors—homogeneous population.

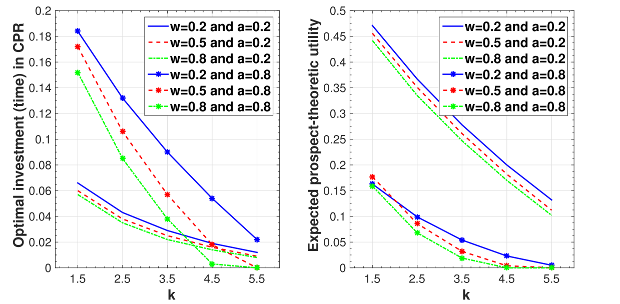


Fig. 10. Visitor optimal investment (left) and visitor expected prospect-theoretic utility (right) versus loss aversion index k—heterogeneous population.

increase in the expected prospect-theoretic utility is observed for the cases with low visitor sensitivity.

In order to further study the effect on competition for CPR exhibits between a single and several self-interested visitors, we use the fragility under competition (FuC) metric defined as the ratio of the fragility of CPR when there are several visitors to the fragility of CPR when there are only one visitor [26]. The fragility of CPR exhibits is expressed by the failure probability function, $p(t_T)$ which steadily increases as visitor total investment t_T increases. Specifically, the FuC is given by $FuC = (p(t_T^*)/p(t_i^*))$, where $p(t_T^*)$ is the failure probability function when the total investment in the CPR at the PNE point of N, $N \geqslant 2)$ homogeneous visitors is t_T^* whereas $p(t_i^*)$ is the failure probability function of a visitor $i, i \in \aleph$ with $N = 1$ who has the same risk preferences as the homogeneous group and his optimal investment in CPR is t_i^*.

Fig. 9 depicts that the FuC of CPR exhibits rises as the number of visitors grows, then depending on the sensitivity parameter a, it reaches a peak and after that remains stable, regardless of the number of visitors. Based on Theorem 1, the total investment in CPR at the PNE is smaller than t_{thres}, $(t_T^* < t_{\text{thres}})$, while assumption 1 states that failure probability is an increasing function of t_T, and thus $p(t_T^*) < p(t_{\text{thres}})$. As a consequence, FuC is upper bounded by the factor $(p(t_{\text{thres}})/p(t_i^*))$ which is clearly confirmed by our numerical evaluation results. Fig. 9 also illustrates that the FuC bound increases when visitors have a smaller sensitivity parameter a, thus becoming more risk-averse in gains and risk seeking in losses. This is justified by the fact that the bounds are only influenced by the sensitivity parameter and they are independent of the loss aversion index and CPR characteristics.

B. Heterogeneous Population

In this section, we move away from the homogeneity assumption with respect to the visitor's behavior, and investigate their decision making process under the presence of heterogeneity in their behavioral pattern in terms of loss aversion and sensitivity. Specifically, we evaluate the visitor satisfaction as expressed via the expected prospect-theoretic utility under such mixed and more realistic scenarios, and investigate how these visitor behavioral parameters influence and guide their final decision about the optimal time investment.

1) Heterogeneity in Loss Aversion: Fig. 10 demonstrates how heterogeneity in loss aversion indices influences visitor investment in CPR exhibits, by considering and observing five visitors for whom though the sensitivity parameter a is identical, they still differ in their attitudes toward loss. The horizontal axis corresponds to the five different visitors with increasing value of their loss aversion parameter k.

The results demonstrate that both visitor investment in CPR and corresponding expected prospect-theoretic utility steadily decreases as loss aversion increases. This trend is caused by the growing importance the visitor assigns to losses as k increases. Furthermore, the results confirm that if a visitor has lower loss aversion than another visitor, then the investment of the former will be at least as high as the latter visitor's investment. This is justified by the fact that the effective rate of return f and its derivative f' are decreasing as influenced by the loss aversion index. Moreover, it is clearly illustrated that visitors with higher sensitivity parameter a, invest noticeably higher amount of time in CPR exhibits while gaining significantly less satisfaction compared to visitors with lower sensitivity parameter a. It is also interesting to notice that the impact of parameter a is greater for visitors with higher loss aversion. Finally, it can be observed that the visitor who has low interest in safe exhibits while has increased both sensitivity and loss aversion parameters, prefers to invest entirely in safe sources. In other words, loss-averse visitors get driven out of the CPR by gain seeking visitors.

Fig. 11 illustrates how visitor heterogeneity in loss aversion affects the fragility of a CPR. The results presented in this figure compare a scenario where five visitors have identical both risk parameters a and k (homogeneous scenario), against a scenario where the five visitors though have identical sensitivity parameter a, they have different loss aversion indices (heterogeneous scenario). For a fair comparison, in the homogeneous group of visitors (former scenario), we use the mean loss aversion index of the heterogeneous society. Based on the corresponding results, we observe that the investment in a CPR is slightly increased when the visitors have a different attitude toward losses compared to the case that all visitors have the same value for parameter k. Consequently, we can

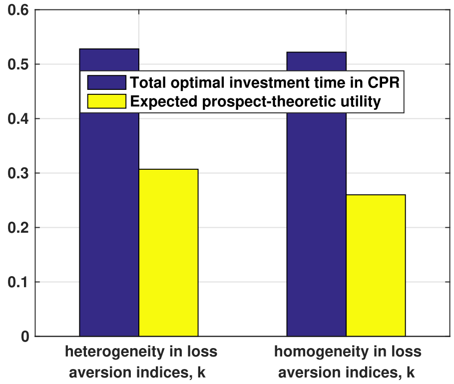


Fig. 11. CPR fragility for visitors with heterogeneous versus homogeneous loss aversion indices.

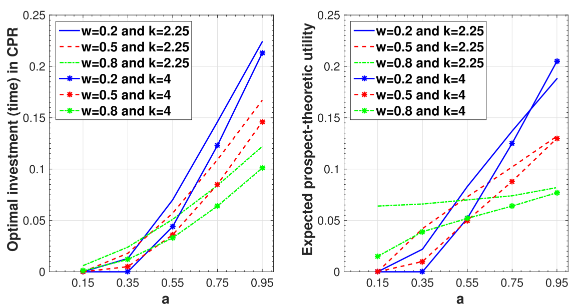


Fig. 12. Visitor optimal investment (left) and expected prospect-theoretic utility (right) versus sensitivity parameter a—heterogeneous population.

argue that the fragility of a CPR increases when visitors are heterogeneous in loss aversion.

2) Heterogeneity in Sensitivity: Fig. 12 shows how heterogeneity in sensitivity parameter a influences visitors investment in a CPR, as well as corresponding visitors, expected prospect-theoretic utility. We consider five visitors who have identical loss aversion but are characterized by different sensitivity parameter a (horizontal axis). The results depict that visitors with higher parameter a invest more in a CPR and consequently obtain higher utility. As far as parameter k is concerned, we notice that as k increases, both time investment and expected prospect utility decrease.

Finally, Fig. 13 demonstrates how heterogeneity in sensitivity parameter a influences the fragility of CPR exhibits. The results presented in this figure compare a scenario of five homogeneous visitors (i.e., same parameters a and k for all visitors) against a scenario where the five visitors have identical loss aversion index k, but different sensitivity parameter values. For a fair comparison, all the visitors of the homogeneous group are assigned a sensitivity parameter equal to the average sensitivity parameter value of all the members of the heterogeneous group. The graph illustrates that the heterogeneity in sensitivity parameter a causes an increase in the CPR investment and consequently an increase in the CPR fragility. Therefore, the heterogeneity in either loss aversion k or sensitivity parameter a leads to the increase of the fragility of CPR exhibits.

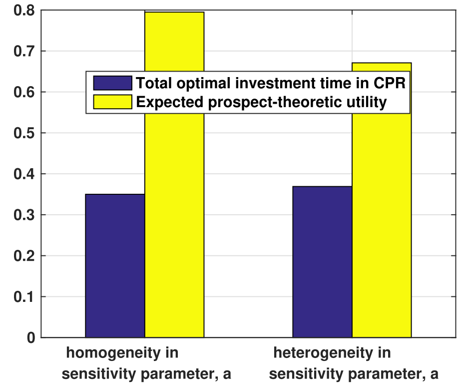


Fig. 13. CPR fragility for visitors with heterogeneous versus homogeneous sensitivity parameter a.

C. Discussion and Guidelines

Based on the results we obtained, we concluded the following outcomes and guidelines reflecting both the cultural heritage site point of view and the individual visitor behavior and satisfaction from their visiting experience.

1) From the cultural heritage site operator point of view, it is clearly more beneficial to have visitors with small sensitivity parameter a, as they gain high satisfaction though they tend to invest less time in their visit at a CPR. As a natural intuitive outcome of such an observation under the assumption of population with smaller sensitivity parameter a, a larger number of visitors can be supported and served, still completing the tour with high satisfaction. People with high sensitivity parameter a present overall a more risk neutral behavior. Consequently, their increased time investment in CPR exhibits results in reduced availability of CPR exhibits to the rest of the visitors, thus increasing the probability of its failure, which in turn leads to a large number of unsatisfied visitors.
2) With reference to loss aversion parameter k, a cultural heritage site should be more keen on servicing visitors with medium loss aversion values. Nevertheless, having to choose between visitors with high and low loss aversion values, the results reveal that the former visitors are more profitable for the cultural heritage site operator. They do significantly shorter visits, while their expected prospect-theoretic utility is comparable to the latter visitors who spend more time observing CPR exhibits, thus causing higher congestion.
3) A significant diversity of visitor interest in safe exhibits causes CPR failure, especially in the case that visitors are characterized by high sensitivity parameter a. The CPR failure can be better prevented if accommodating visitors with lower sensitivity parameter a, since in that case, visitors tend to invest less amount of time in the CPR exhibits. It is interesting to note that CPR failure cannot be avoided, if visitors experience higher loss aversion (as denoted through parameter k), instead of lower sensitivity parameter a, because though the total

time investment in CPR decreases, the social optimum t_{thres}, decreases as well.

4) Visitor heterogeneity in either loss aversion or sensitivity parameter increases the probability of CPR failure.
5) An interesting outcome of our model and study is the observation that when a visitor i has lower loss aversion than a visitor j, that is: $k_i < k_j$, then the investment of the former will be at least as high as the latter visitor's investment, $t_i \geqslant t_j$.
6) A visitor with high loss aversion k experiences significant disutility in case of a loss, and consequently this dissatisfaction prevents him from investing in more risky options. Such a type of visitor prefers to invest a limited amount of time in CPR exhibits, and the rest of his time in safe exhibits.
7) A visitor with high sensitivity parameter a becomes more difficult to be satisfied compared to a visitor with lower sensitivity parameter. Assuming that the former visitor apart from the increased sensitivity parameter is also characterized by low interest w in safe exhibits—which essentially denotes that he gets relatively low satisfaction form them—he will invest a considerable amount of time in CPR exhibits in order to increase his satisfaction.

VI. Conclusion

In this paper, a solution-driven approach toward understanding the visitors' behavior within cultural heritage spaces, while obtaining their optimal visiting time investment under realistic risky considerations and maximize their perceived satisfaction was provided. Specifically, we considered the formulation, quantification, and evaluation of visitor realistic behavior via properly capturing their loss aversion and gain seeking characteristics within the cultural heritage environments. Our goal was to determine the visitor optimal visiting time investment to a different type of exhibits. Toward achieving this goal, the fundamental concepts of prospect theory were adopted and aligned to the problem of formulating visitor QoE optimization. The exhibits were organized in two main categories, i.e., safe exhibits and CPR exhibits, based on their popularity and attractiveness to the visitors. The visitors were assumed to adopt appropriately formulated prospect-theoretic utility functions, which consider visitor actual utility, their visiting time investment and their behavior under risks.

Taking into account the potential interdependence of visitors' decisions, a noncooperative game among visitors was formulated and solved in a distributed manner in order to maximize each visitor's prospect-theoretic utility function. Detailed numerical results were presented highlighting the operation and superiority of the proposed framework, while providing useful insights about visitor decisions under realistic conditions and behaviors, within such a competitive interdependent social system.

Our current and future research work focuses on treating the overall key problem of congestion management in various cultural heritage sites, which has emerged as one of high research interest and practical importance for both cultural heritage site operators and visitors themselves. Following prospect theory principles that allow for a more realistic modeling of visitors behavior and pattern, we plan to further study several interesting processes affecting visitors touring experience, ranging from pricing policies as a mechanism to reduce the probability of CPR failure, to visitors route choice behavior, which significantly affects their perceived satisfaction. Moreover, it is of high practical significance to investigate how framing effects can influence or even drive visitors route and overall touring decisions, by appropriately and intelligently providing people with options within the context of a specific frame, while at the same time enable cultural heritage site operators to properly plan the visiting traffic within the cultural heritage site.

Appendix A
Proof of Theorem 1

Toward proving the existence of a PNE $t_i^* = B_i(t_{-i}), t_i^* \in [0, 1)$ of the noncooperative game $G = [N, \{T_i\}, \{\mathbb{E}(u_i)\}]$, initially we clarify that the visitor's $i, i \in \aleph$ best response strategy $B_i(t_{-i})$ can be either zero, i.e., $B_i(t_{-i}) = 0$ or a positive value, i.e., $0 < B_i(t_{-i}) < 1$. The best response strategy can never be equal to 1, i.e., $B_i(t_{-i}) = 1$ as in that case $p(1) = 1$ (see Assumption 1) and CPR exhibits fail and the visitor's satisfaction drops. The first-order derivative of the CPR exhibits' effective rate of return is given as follows:

$$\frac{\partial f_i(t_T)}{\partial t_T} = \frac{\partial \overline{r}(t_T)}{\partial t_T}(1 - p(t_T)) - \left(\overline{r}(t_T) + k_i w_i^{a_i}\right)\frac{\partial p(t_T)}{\partial t_T}. \quad (16)$$

Based on Assumption 3, the rate of return function $r(t_T)$ is nonincreasing and concave, therefore, $\overline{r}(t_T)$ is concave decreasing, thus $(\partial \overline{r}(t_T)/\partial t_T) < 0$. Also, $(1 - p(t_T)) > 0$. Moreover, $\overline{r}(t_T)$ is positive, concave, decreasing, and twice continuously differentiable for any $a_i \in (0, 1]$, $w_i \in [0, 1]$ because we have defined $\overline{r}(t_T) = (r(t_T) - w_i)_i^a$ where $r(t_T)$ is concave, decreasing, twice continuously differentiable and greater than 1. The CPR exhibits probability of failure is a strictly increasing function with respect to visitor time investment t_T, thus $(\partial p(t_T)/\partial t_T) > 0$. Therefore, the effective rate of return function is strictly decreasing, i.e., $(\partial f_i(t_T)/\partial t_T) < 0$.

Case A: If $f_i(t_T = 0) \leqslant 0$, then the investment of visiting time at CPR exhibits is not profitable for visitors, thus, $B_i(t_{-i}) = 0$. In this case, there does not exist a threshold value $t_{\text{thres}} \in [0, 1]$ such that $t_{-i} \geqslant t_{\text{thres}}$, as $t_{-i} \equiv t_{\text{thres}} = 0$. If $f_i(t_T = 0) > 0$ based on (11), we have $f_i(t_T = 1) = -k_i w_i^{a_i} < 0$, thus based on the intermediate value theorem, there exists a value $t_{\text{thres}}, t_{\text{thres}} \in [0, 1]$ such that $f_i(t_{\text{thres}}) = 0$, as presented in Fig. 14.

Thus, when $t_T \geqslant t_{-i} > t_{\text{thres}}$, the best response strategy of visitor i is $B_i(t_{-i}) = 0$, otherwise, if he invests part of his visiting time at CPR exhibits, i.e., $B_i(t_{-i}) > 0$ then his expected prospect-theoretic utility as expressed in (11) will be negative $f_i(t_T) < 0$ (see Fig. 14). In this case, i.e., $t_T \geqslant t_{-i} > t_{\text{thres}}, t_{\text{thres}} \in [0, 1]$ the best response strategy is unique, i.e., $B_i(t_{-i}) = 0$. Thus, the PNE exists and is given by $t_i^* = B_i(t_{-i}) = 0$.

Case B: Examining the remaining case, i.e., $t_{-i} \leqslant t_T < t_{\text{thres}}$ based on the above-mentioned analysis and Fig. 14,

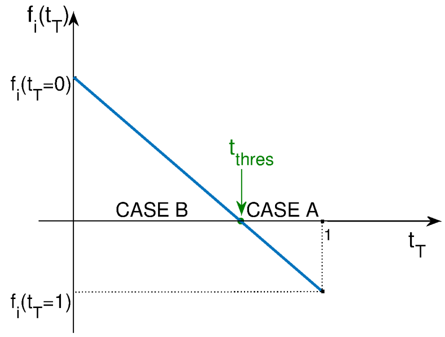


Fig. 14. Effective rate of return function.

we have $f_i(t_T) > 0$. Thus, based on (11), we have $\mathbb{E}(u_i) = t_i^{a_i} f_i(t_T) > 0$. Therefore, the best response strategy is strictly positive, i.e., $0 < B_i(t_{-i}) < 1$, if $t_{-i} \leqslant t_T < t_{\text{thres}}$. Given the latter constraint, it holds true that $[B_i(t_{-i}) + t_{-i}] \in (0, t_{\text{thres}}), \forall B_i(t_i) \in (0, 1)$ since the expected prospect-theoretic utility [(11)] must be positive (i.e., $f_i(t_T) > 0$ in case B of Fig. 14) at the nonzero best response strategy. In this case, i.e., $t_{-i} \leqslant t_T < t_{\text{thres}}$, we prove the existence of a positive best response strategy, i.e., $0 < B_i(t_{-i}) < 1$. Thus, the PNE exists and $t_i^* = B_i(t_{-i}) \in (0, 1)$.

The third property of Theorem 1 can be easily concluded from the above-mentioned analysis and it is illustrated in Fig. 14.

Appendix B
Proof of Lemma 1

Based on Theorem 1, case A (see Appendix A), we have shown that the best response strategy is single valued, i.e., $B_i(t_{-i}) = 0$, if $t_T \geqslant t_{-i} > t_{\text{thres}}$, where $t_{\text{thres}} \in [0, 1]$. Thus, in the following, we examine the case where $t_{-i} \leqslant t_T < t_{\text{thres}}$, that we have already shown that there exists at least one best response strategy, i.e., $0 < B_i(t_{-i}) < 1$. Given that there exists at least one best response strategy $B_i(t_{-i})$, it should be one of the solutions of the expected prospect-theoretic utility's first-order derivative, which is given as follows:

$$\begin{aligned}\frac{\partial \mathbb{E}(u_i)}{\partial t_i} &= a_i t_i^{a_i-1} f_i(t_T) + t_i^{a_i} \frac{\partial f_i(t_T)}{\partial t_T} \\ &= \left[t_i^{a_i} \frac{\partial \overline{r}(t_T)}{\partial t_T} + a_i \overline{r}(t_T) t_i^{a_i-1}\right](1 - p(t_T)) \\ &\quad - t_i^{a_i} \overline{r}(t_T) \frac{\partial p(t_T)}{\partial t_T} \\ &\quad - k_i \left[a_i w_i^{a_i} t_i^{a_i-1} p(t_T) + w_i^{a_i} t_i^{a_i} \frac{\partial p(t_T)}{\partial t_T}\right]. \end{aligned} \tag{17}$$

It is noted that $-t_i^{a_i} \overline{r}(t_T)(\partial p(t_T)/\partial t_T) < 0$ and $-k_i[a_i w_i^{a_i} t_i^{a_i-1} p(t_T) + w_i^{a_i} t_i^{a_i}(\partial p(t_T)/\partial t_T)] < 0$. Thus, in order to determine the root of (17), it should hold true that

$$\left[t_i^{a_i} \frac{\partial \overline{r}(t_T)}{\partial t_T} + a_i \overline{r}(t_T) t_i^{a_i-1}\right] > 0. \tag{18}$$

Calculating the second derivative of $\mathbb{E}(u_i)$, we have the following expression:

$$\begin{aligned}&\frac{\partial^2 \mathbb{E}(u_i)}{\partial t_i^2} \\ &= \left[t_i^{a_i} \frac{\partial^2 \overline{r}(t_T)}{\partial t_T^2} + 2a_i t_i^{a_i-1} \frac{\partial r(t_T)}{\partial t_T}\right](1 - p(t_T)) \\ &\quad - 2\left[t_i^{a_i} \frac{\partial \overline{r}(t_T)}{\partial t_T} + a_i t_i^{a_i-1} \overline{r}(t_T)\right] \frac{\partial p(t_T)}{\partial t_T} \\ &\quad - t_i^{a_i} \overline{r}(t_T) \frac{\partial^2 p(t_T)}{\partial t_T^2} \\ &\quad - k_i \left[2a_i w_i^{a_i} t_i^{a_i-1} \frac{\partial p(t_T)}{\partial t_T} + w_i^{a_i} t_i^{a_i} \frac{\partial^2 p(t_T)}{\partial t_T^2}\right] \\ &\quad + a_i(a_i - 1) t_i^{a_i-2}\left[\overline{r}(t_T)(1 - p(t_T)) - k_i w_i^{a_i} p(t_T)\right]. \end{aligned} \tag{19}$$

Given that $0 < a_i \leqslant 1$, $f_i(t_T) > 0$ and $\overline{r}(t_T)$ is concave decreasing, we conclude from (19) that $(\partial \mathbb{E}(u_i)^2/\partial t_i^2) < 0$, thus the expected prospect-theoretic utility is concave with respect to t_i. Moreover, given that $\overline{r}(t_T)$ is concave decreasing, the function from the inequality (18), i.e., $t_i^{a_i}(\partial \overline{r}(t_T)/\partial t_T) + a_i \overline{r}(t_T) t_i^{a_i-1}$, is decreasing with respect to t_i. For small values of t_i, i.e., $t_i \to 0$ and $t_{-i} < t_{\text{thres}}$, it holds true that $t_i^{a_i}(\partial \overline{r}(t_T)/\partial t_T) + a_i \overline{r}(t_T) t_i^{a_i-1} > 0$. We define $s \overset{\Delta}{=} \sup\{t_i \in [0, 1) | t_i^{a_i}(\partial \overline{r}(t_T)/\partial t_T) + a_i \overline{r}(t_T) t_i^{a_i-1} > 0\}$ thus the inequality (18) holds true only in the interval $[0, s]$. Thus, the expected prospect-theoretic utility function has a unique maximum in the interval $[0, s] \subseteq [0, 1)$. Therefore, the best response strategy is single valued.

Appendix C
Proof of Theorem 2

The proof of Theorem 2 is based on the reduction to absurdity. We assume that there exist two pure Nash equilibria for each visitor, i.e., $t_{i,1}^*$ and $t_{i,2}^*$ resulting in two different total investments $t_{T,1}^*$ and $t_{T,2}^*$. Without loss of generality, we assume that $t_{T,1}^* < t_{T,2}^*$. Similar analysis can be followed if $t_{T,1}^* > t_{T,2}^*$. We define the set $S \overset{\Delta}{=} \{i \in \aleph \mid t_T^* < t_{\text{thres}}\}$, i.e., the set of all visitors with positive best response strategy. Thus, we have $S_2 \subseteq S_1$. Therefore, based on (15), we have $\sum_{i \in S_1} g_i(t_{T,1}^*) = t_{T,1}^*$ and $\sum_{i \in S_2} g_i(t_{T,2}^*) = t_{T,2}^*$. Given that $S_2 \subseteq S_1$, we can rewrite $\sum_{i \in S_1} g_i(t_{T,1}^*) = t_{T,1}^*$ as $\sum_{i \in S_2} g_i(t_{T,1}^*) + \sum_{i \in S_1 \setminus S_2} g_i(t_{T,1}^*) = t_{T,1}^*$. Thus, we have $\sum_{i \in S_2} g_i(t_{T,1}^*) \leqslant t_{T,1}^* < t_{T,2}^* = \sum_{i \in S_2} g_i(t_{T,2}^*)$. Based on Lemma 1, we conclude to $g_i(t_{T,1}^*) > g_i(t_{T,2}^*)$ $\forall i \in S_2$, if $t_{T,2}^* > t_{T,1}^*$, which is a contradiction. Thus, the PNE is unique.

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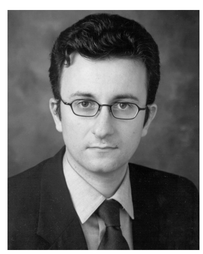

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